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Role of Compound Nuclei in Intermediate Energy Heavy Ion Reactions

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Role of Compound Nuclei in Intermediate Energy Heavy Ion Reactions

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Abstract: The presence of compound nuclei in the exit channels of many intermediate energy reactions is reviewed. The statistical decay of such compound nuclei may be responsible for many of the observed features. The role of compound nuclei in complex fragment production, multifragmentation and high energy gamma-ray emission is illustrated.

Introduction

Present attempts to clarify the reaction mechanisms prevailing at intermediate energies seem to suffer from two prejudices both associated with the jump in energy that the field has forced upon some of us. The first prejudice stems from the legacy of our low energy experience. We are very familiar with the standard mode of formation of compound nuclei through complete fusion, and with their decay by the dominant channels, like light particle evaporation and fission. However, the fact that at higher energies compound nuclei may be formed in less conventional ways, or that they may decay by unusual channels does not seem to occur immediately to our attention.

The second prejudice is due to our excessive expectations. We are so attuned to searching for new mechanisms which we expect to be prompt, or fast, or dynamically controlled, that we tend to forget about "conventional mechanisms" which dominate at low energies but may be quite alive and well even at higher energies. These mechanisms, insofar as we know, may be responsible for all that we have observed so far or, at the very least, may provide a substantial background on top of which the "novel" effects must ride.

The consequences of this state of affairs is similar to that resulting from "weak" interactions with new and exotic lands. As exemplified in the "Bestiaria" of the Middle Ages or in the "Natural History" of Pliny the Elder:

1) Everything is anecdotal; one experiment and we are off to a new land.
2) Everything is new and different; otherwise we do not feel justified in our "modus operandi".
3) A rigid and restricted view of what is normal is held; this is to insure point 2.
4) Complexity is confused with novelty; the fact that we do not understand immediately what is

going on means that it must be new. The more complicated, of course, the better.

In order to illustrate the generalities presented above, let us consider, as examples the following topics which are of some relevance today:

1) Complex particle production
2) Multifragmentation and nuclear comminution
3) γ-ray emission

In what follows you may be reminded at times of Don Quixote who saw liquid-vapor equilibrium, multifragmentation, n-p bremsstrahlung and other marvels every day, and of Sancho Panza, who in his simplicity could only see compound nucleus decay. Despite your inclinations and sympathies, you should try and decide which of the two, the hero or the antihero, is right.

About Compound Nuclei And New Ways of Forming Them

At low energies we are used to preparing compound nuclei by means of fusion reactions; after all, it is not an accident that compound nuclei are called compound. However, what Bohr had in mind when he introduced this new concept was not the particular way in which the compound nucleus was formed. To the contrary he insisted that, due to total relaxation of the system, all the dynamical information associated with the entrance channel was forgotten, and that the decay could only depend upon the statistical features of the available exit channels. In order to prove that it does not matter how the compound nucleus is formed, the early and not so early literature is rich with examples of different "fusion" channels leading to the same compound nucleus - which does indeed decay always in the same way. So, the essence of the compound nucleus is **not** in the fusion of target and projectile but in the **decoupling** of Entrance and Exit Channels.

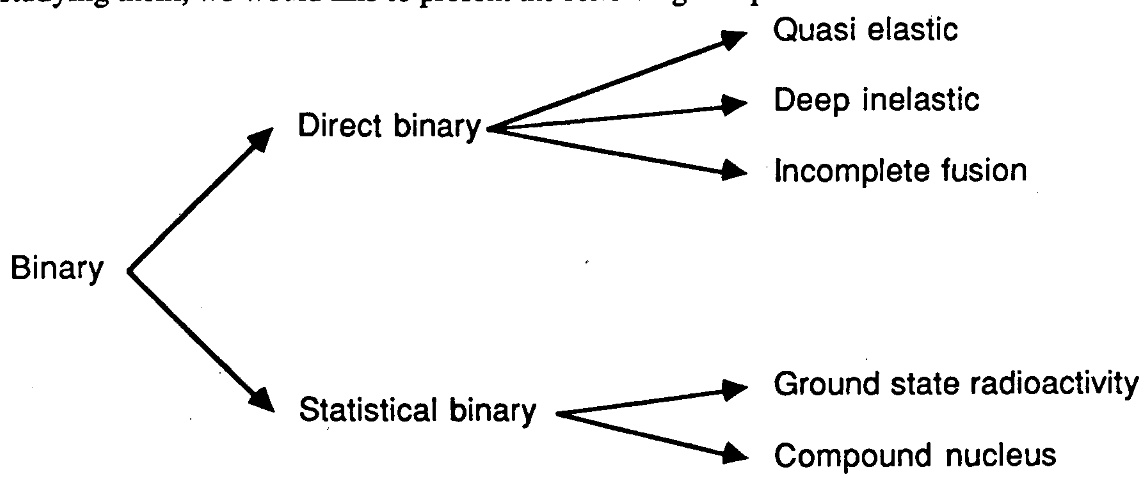
Having accepted that, we realize that compound nuclei may be more common than previously thought. For instance:

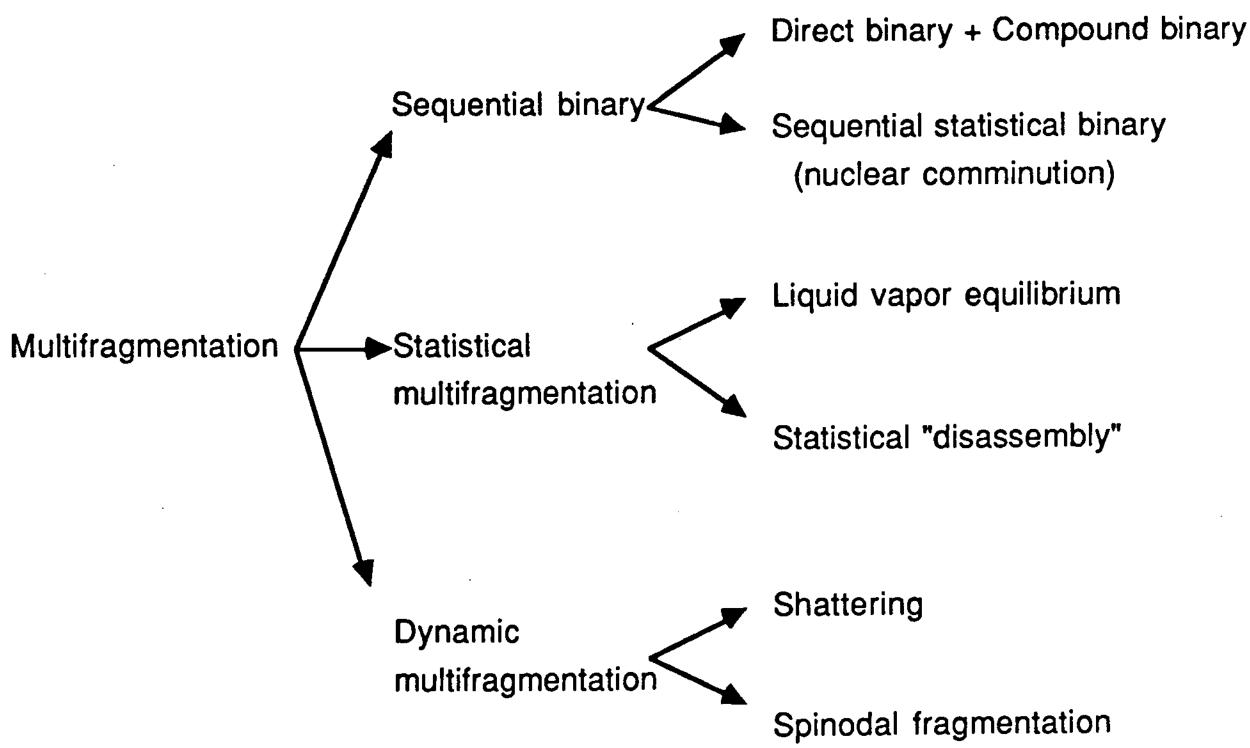
1) The residue product after a compound nucleus evaporates a particle is still a compound nucleus.
2) The two fragments produced in fission do relax and eventually evaporate neutrons as compound nuclei.
3) Quasi elastic and Deep Inelastic heavy ion reactions produce fragments which also relax into compound nuclei and decay as such.
4) In the process of incomplete fusion both the incomplete fusion product and the spectator do eventually relax into compound nuclei.
5) In the fireball production mechanism, the two spectator fragments are expected to relax into compound nuclei, and even the fireball may not be far from a compound nucleus, either.

As a conclusion, it seems advisable to inspect exit channels for the possible presence of compound nuclei. A lot of the particles observed may well be coming from them!

Complex Fragment Production

In view of the many fragments observed in intermediate energy reactions and of the many authors studying them, we would like to present the following comprehensive classification.[1)]





We shall see which of the above ways Nature decided to choose in order to produce complex fragments.

With the advent of intermediate energies, complex fragments have become a very pervasive presence. Where could they possibly come from? Conventional wisdom held that compound nuclei decay either by n, p, and α emission or by fission. As a consequence, complex fragments could only come from some other novel mechanism, like liquid vapor equilibrium, multifragmentation, etc.[1)] However, it has been shown that compound nuclei at low energy can emit complex fragments.[2)] In fact, it is possible to consider light fragment emission and fission as the two extremes of a single mode of decay, connected by the mass asymmetry degree of freedom.[3)] This process allows for the decay by emission of complex fragments and the rarity of its occurence is due to the important but accidental fact that the barrier associated with such an emission is quite high.

Let us consider the potential energy surface of a nucleus as a function of a suitable set of deformation coordinates. This surface is characterized by the ground state minimum and by the fission saddle point. We can cut this surface with a line passing through the fission saddle point along the mass asymmetry coordinate in such a way that each of its points is a saddle point if one freezes the mass asymmetry coordinate. The locus of all these conditional saddle points we call the "ridge line".[3)] Fig. 1 shows two examples of this line, one for a light system below the Businaro-Gallone point and the other for a heavier system above the Businaro-Gallone point. The same figure shows the expected particle yield following the statistical prediction:

$$Y(Z) \propto \exp[-V(Z)/T].$$

One can make three observations:

1) The systems below the Businaro-Gallone point give rise to a U-shaped mass or charge distribution with a minimum at symmetry.
2) The systems above the Businaro-Gallone point give rise to a similar distribution but with a maximum (fission peak) growing in at symmetry.
3) The yield increases with temperature and the yield associated with the highest barriers increases the fastest.

Consequently complex fragments, although very rare at low energy, become rapidly abundant at high energies. The existence of this compound nucleus mechanism at low energies has been proven in detail.[2)] Could the fragments observed at higher energies arise from the same mechanism?

In experiments up to 50 MeV/u,[4)] we have been able to identify three kinds of sources of complex fragments, which turn out to be rather conventional. The three sources are:

1) Quasi elastic/deep inelastic scattering.
2) Spectators in incomplete fusion processes.

3) Compound nucleus.

The first two sources produce fragments which are target and/or projectile related. The third is just the high energy version of the low energy compound nucleus decay. How can these three sources be distinguished? We have found that reverse kinematics and very asymmetric target-projectile combinations are particularly useful for a series of reasons. The principal reasons are: 1) the quasi elastic/deep inelastic processes and the incomplete fusion spectators are confined to very low atomic numbers leaving the remaining Z-range for compound nucleus products; 2) The associated limited range of impact parameters leads to a corresponding narrow range of momentum transfers and consequently to a small range of source velocities; 3) Reverse kinematics brings all the fragments into a relatively narrow forward cone and boosts their energy, thus greatly simplifying their detection and identification.

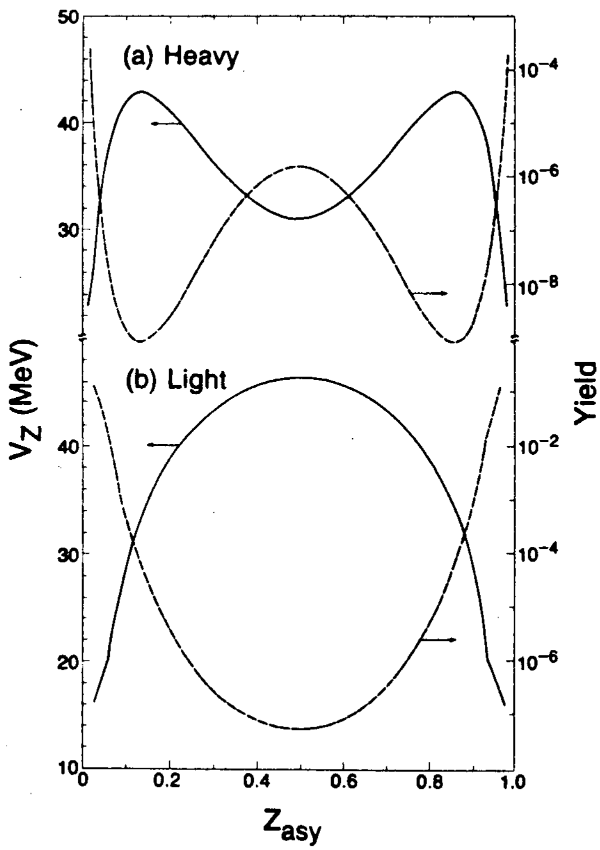


Fig. 1 Schematic ridge line potentials (solid curve) and calculated yields (dashed curve) for: a) a heavy CN above the Businaro-Gallone point; and b) a light CN below the Businaro-Gallone point as a function of the mass asymmetry coordinate (Z_{asy}).

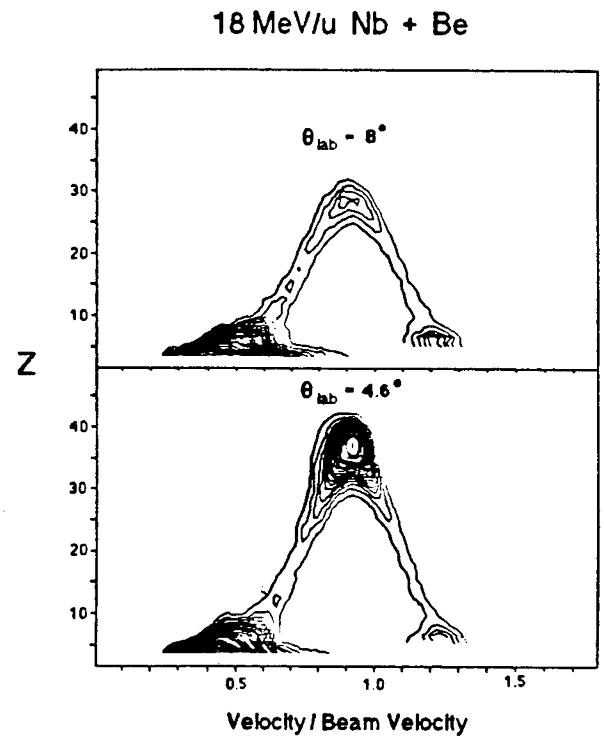


Fig. 2 Contours of the invariant cross section in the Z - velocity plane for complex fragments emitted from the 18 MeV/u ^{93}Nb + ^{9}Be reaction at θ_{lab} = 4.6° and 8°. The "big foot" visible at low velocities for Z < 10 is attributed to quasi elastic and deep inelastic products.

The evidence of the compound nucleus origin of these fragments can be seen in the plots of the cross section in the velocity - atomic number plane like that shown in Fig. 2. The two legs of the lambda pattern represent the upper and lower solutions in reverse kinematics associated with the binary decay of the source, and correspond to the Coulomb circles visible in the $v_{||}$ - $v_{\perp}$ plane for each Z value.[1)] The telltale signature of a binary decay is not only the presence of a sharp Coulomb circle, but the fact that its radius decreases with increasing Z value as required by momentum conservation. The large cross sections observed at low Z values and attached to the low velocity branch (big foot) are associated with quasi and deep inelastic products. The choice of very asymmetric target projectile combinations shows here its wisdom. The more symmetric the

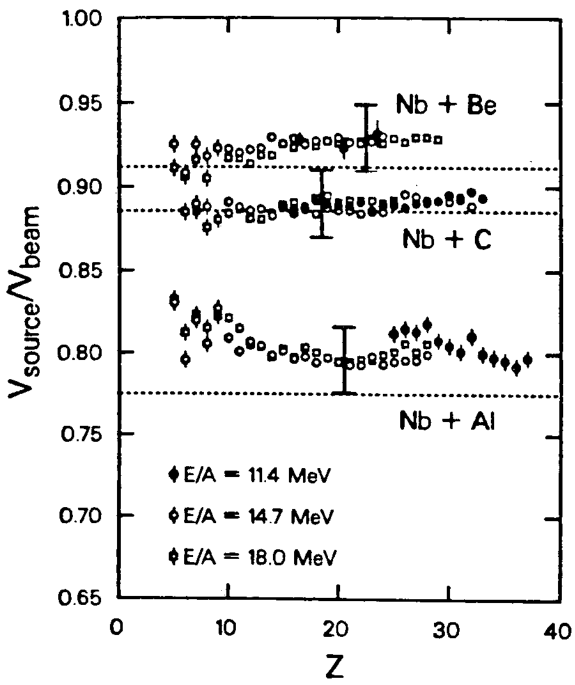


Fig. 3 Source velocities extracted from the Coulomb ring of each Z-species produced in the reactions 11.4, 14.7 and 18.0 MeV/u ^{93}Nb + ^{9}Be,^{12}C & ^{27}Al reactions. The small error on each point represents the statistical error associated with the extraction process. The large squared error bars indicate the possible systematic error. Note the suppressed zero on the abscissa. Although there is a small systematic deviation of the measured velocities above the complete fusion velociy, the lack of energy dependence of this effect suggests that complete fusion has taken place.

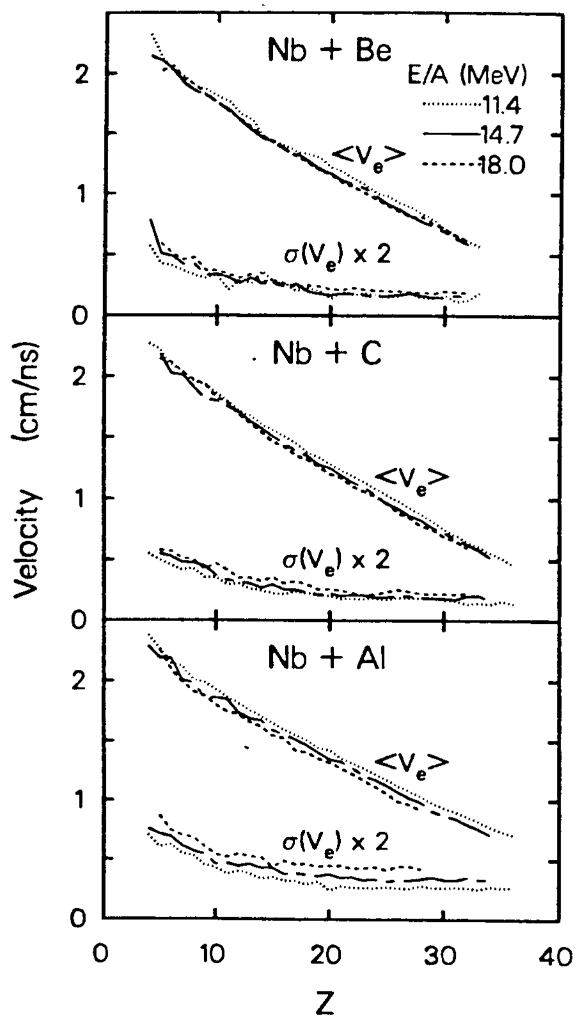


Fig. 4 First and second moments of the velocity spectra for each Z-species produced in the 11.4, 14.7 and 18.0 MeV/u ^{93}Nb + ^{9}Be,^{12}C & ^{27}Al reactions. To show the three bombarding energies on the same plot, lines are used rather than the data points.

target-projectile combination is, the more extensive the obscuration of the compound nucleus component by quasi - deep inelastic fragments is expected to be.

The centers of the circles give the source velocities which, as shown in Fig. 3 are remarkably independent of the fragment Z value and correspond to either complete or incomplete fusion of the light target with the heavy projectile.

The radii of the circles, plotted vs fragment atomic number demonstrate with their nearly linear dependence vs Z their Coulomb origin as shown in Fig. 4.

The cross sections and their dependence upon energy and fragment atomic number are of particular importance to demonstrate their compound nucleus origin. When a compound nucleus is about to decay, it is offered many channels which will be choosen proportionally to their associated phase space. In particular, neutron, proton, and alpha decay, because of their small associated barriers are the dominant decay channels with which complex fragments must compete. Thus the cross section associated with the emission of any given fragment reflects this competition. In Fig. 5 an example of absolute charge distributions is given, together with a calculation performed with a compound nucleus decay code (GEMINI)[4)] which follows the decay of the compound nucleus through all the channels including complex fragment emission. The code reproduces the absolute cross sections and their charge and energy dependence very accurately, thus confirming compound nucleus decay as the dominant mechanism in this energy range.

Coincidence data confirm the binary nature of the decay. The Z_1 - Z_2 scatter plots (see Fig. 6) show the diagonal band characteristic of binary decay. The hatched area is the predicted locus of events after correcting for sequential evaporation from the primary fragments. The spectra associated with the sum $Z_1 + Z_2$ show a rather sharp peak very near the value of Z_{total} indicating again that there is only a small charge loss and that most of the total charge available in the entrance channel is to be found in the two exit channel partners.

All the evidence produced above is but a small sample of the evidence available for compound nucleus emission of complex fragments at bombarding energies up to 50 MeV/u. So far binary decay has dominated the scene while multifragmentation has been conspicuously absent. Yet it is not unreasonable to envision at even higher energies exit channels presenting more than two main fragments. Does that mean, automatically, that the role of the compound nucleus is over? Most likely not.

Multifragmentation and Nuclear Comminution

The evidence presented so far illustrates the emission of complex fragments through binary compound nucleus decay. If there is enough excitation energy available, the primary fragments are also very excited and can have a significant probability of decaying in turn into two more fragments. In this way, which is a very conventional way, one can foresee one possible

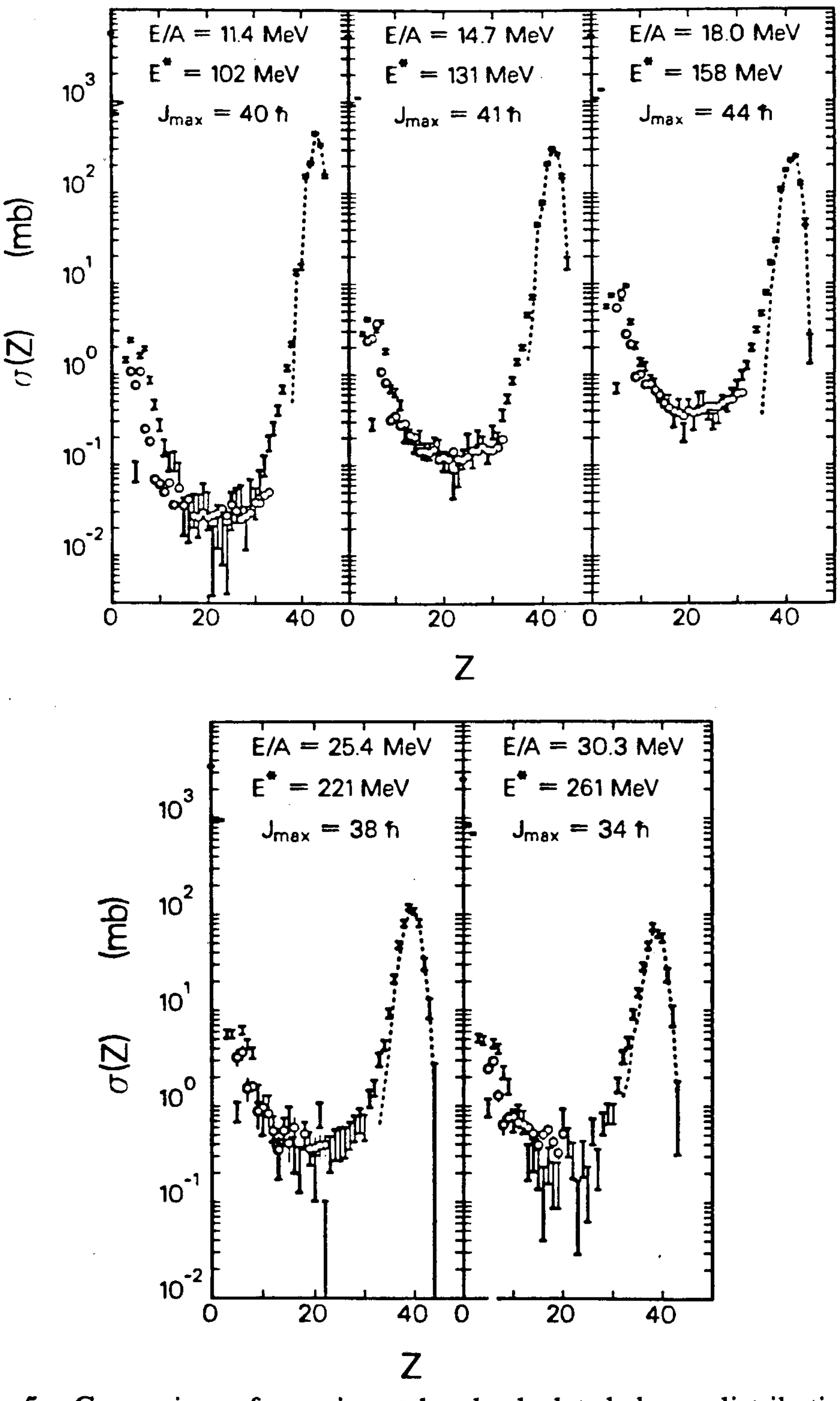


Fig. 5 Comparison of experimental and calculated charge distributions for the ^{93}Nb + ^{9}Be reaction at E/A = 11.4, 14.7, 18.0, 25.4 and 30.3. The experimental data are indicated by the hollow circles and the values calculated with the code GEMINI are shown by the error bars. The dashed curve indicates the cross sections associated with classical evaporation residues which decay only by the emission of light particles ($Z \leq 2$). Note the value of the excitation energy (E^*) corresponding to complete fusion and the value of J_{max} assumed to fit the data.

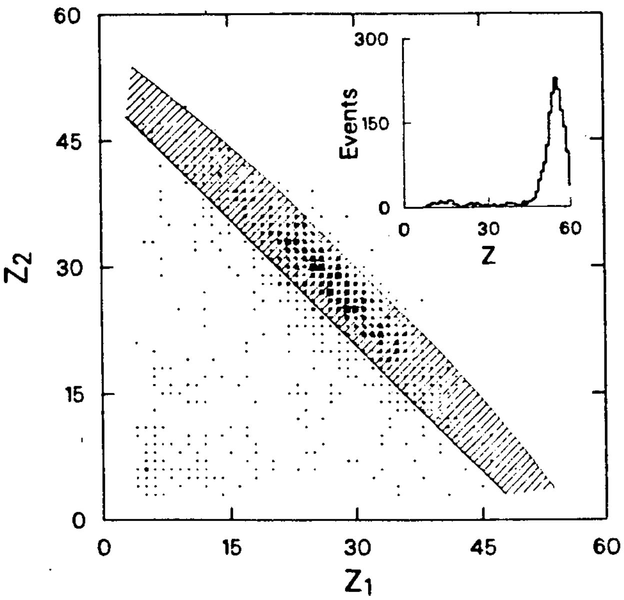


Fig. 6 Scatter plots of the coincidence events, Z_1 - Z_2, detected in the two telescopes on opposite sides of the beam, for the ^{139}La + ^{12}C reaction at 50 MeV/u. The hatched area is the predicted locus of events after correcting for sequential evaporation from the primary fragments. The distributions of the sum of the charges (Z_1 + Z_2) is shown in the inset.

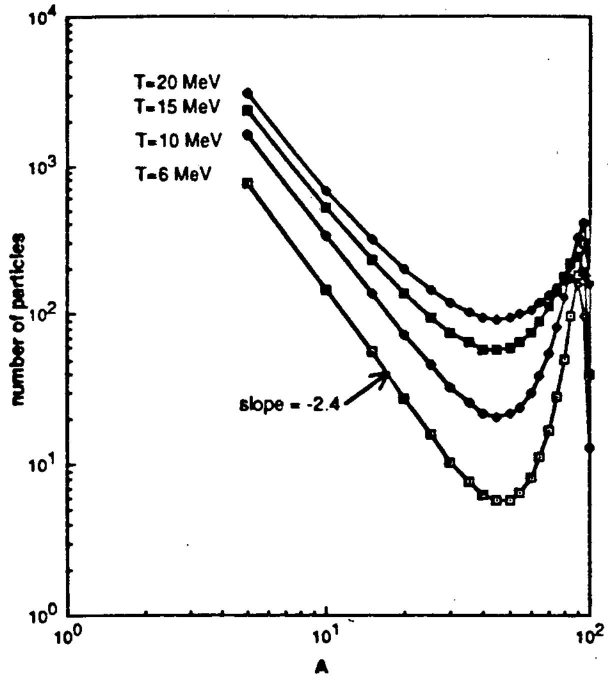


Fig. 7 Theoretical mass distributions from comminution calculations of the dexcitation of a mass 100 compound nucleus at several temperatures. Notice the beautiful power law behavior at small masses.

explanation for multifragmentation, namely that arising from sequential binary decay. We can expect that this mode will be responsible for a predictable and substantial background to other multifragmentation mechanisms if any.

This process of sequential binary decay, controlled at any stage by the compound nucleus branching ratios, we call "nuclear comminution".[1] The calculations of the resulting mass distributions are trivial although tedius and time consuming. We have tried to simulate the process by assuming a potential energy curve vs mass asymmetry (ridge line) with a maximum at symmetry of 40 MeV and with the value of 8 MeV for the extreme asymmetries. The primary yield curve is taken to be of the form:

$$Y(A) = K \exp\left[- V(A)/T(A) \right] . \tag{1}$$

Each of the resulting fragments is assumed to have a similar ridge line and a properly scaled temperature and is allowed to decay accordingly, until all the excitation energy is exhausted. The resulting mass distributions for a series of initial temperatures are shown in Fig. 7. The log-log plots show an exquisite power law dependence for the low masses with exponents around 2.3 - 2.4 which, incidentally, are very close to the exponent expected for the liquid vapor phase transition at the critical temperature. This result shows that a power law dependence is not a unique diagnostic feature of liquid vapor equilibrium, but rather is an apparently "generic" property arising even from sequential binay decay or comminution. A more realistic calculation with the statistical code GEMINI is shown in Fig. 8. Even in this calculation, the power law is evident. With this code it is possible to calculate the excitation energy dependence of the binary, ternary, quaternary decays, etc. as shown Fig. 9. These kinds of excitation functions should be of help in verifying the mechanism of nuclear comminution in the experimental data.

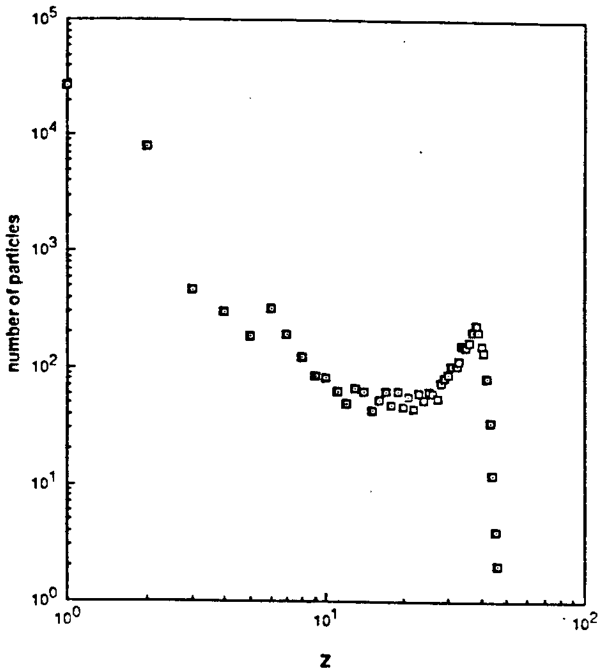


Fig. 8 A plot of the predicted charge distribution associated with the fragments produced in the deexcitation of a ^{139}La compound nucleus at 1100 MeV and J = $50\hbar$. The calculations were done with the statistical model code GEMINI.

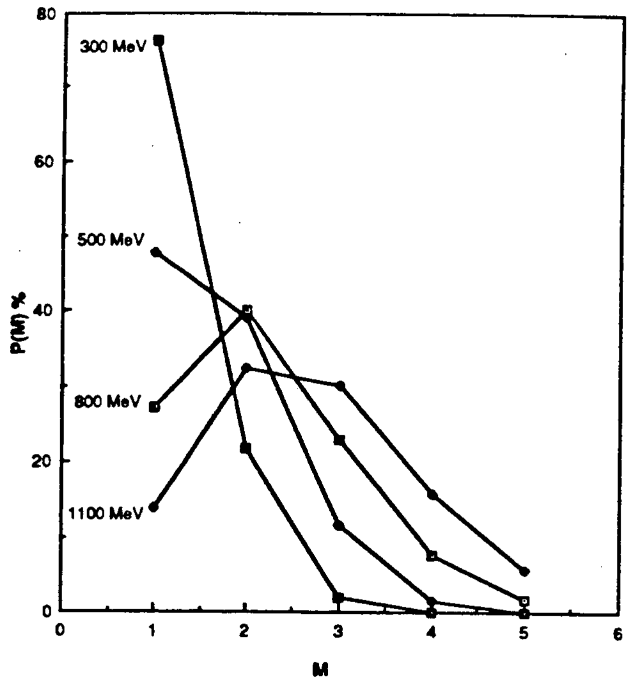


Fig. 9 A plot of the predicted multiplicity distribution of fragments with A > 4 associated with the deexcitation of a ^{139}La compound nucleus at four different excitation energies. The calculations were done with the statistical model code GEMINI.

Statistical γ-ray Emission

High energy γ rays associated with intermediate energy ion reactions were studied initially in order to observe the theoretically predicted "coherent bremsstrahlung"[5,6)] associated with the collective deceleration of the two partners in the collision. Nature's lack of cooperation forced the interpretation of the data back to the less exalted "incoherent nucleon-nucleon bremsstrahlung"[5,6] which had at least the glamour of being associated with the entrance channel. This interpretation is probably correct in many cases. However, in reviewing the data available in the literature, we were struck by the possibility that some of the high energy γ rays could come from some excited compound nuclei present in the exit channel. Unfortunately in all of these experiments the exit channels were too poorly characterized to permit any serious analysis of this sort.

Eventually we found an experiment, ^{100}Mo + ^{100}Mo at 20 MeV/u,[7] where the exit channel was very well characterized. In this reaction the two nuclei undergo a deep inelastic collision. The dissipated energy which may amount to as much as 800 MeV (400 MeV for each fragment!) is disposed of mainly by sequential light particle emission. This emission is a true evaporation from the two deep inelastic fragments and has been studied in detail as a function of exit channel kinetic energy.[8] At times these excited fragments emit complex fragments giving rise to a 3-body and a 4-body exit channel.[9] This emission is also statistical and is in competition with the main decay channels like n, p, and a particle emission. This can be inferred from the probability of 3-body decay as a function of dissipated energy. From this dependence, we can see whether we are dealing with a statistical process. A plot of the log of the probability vs fragment excitation to the -1/2 power should give a linear dependence. This is very clearly visible in Fig. 10, where the data were taken from three different bombarding energies for the same reaction. All this is to prove that

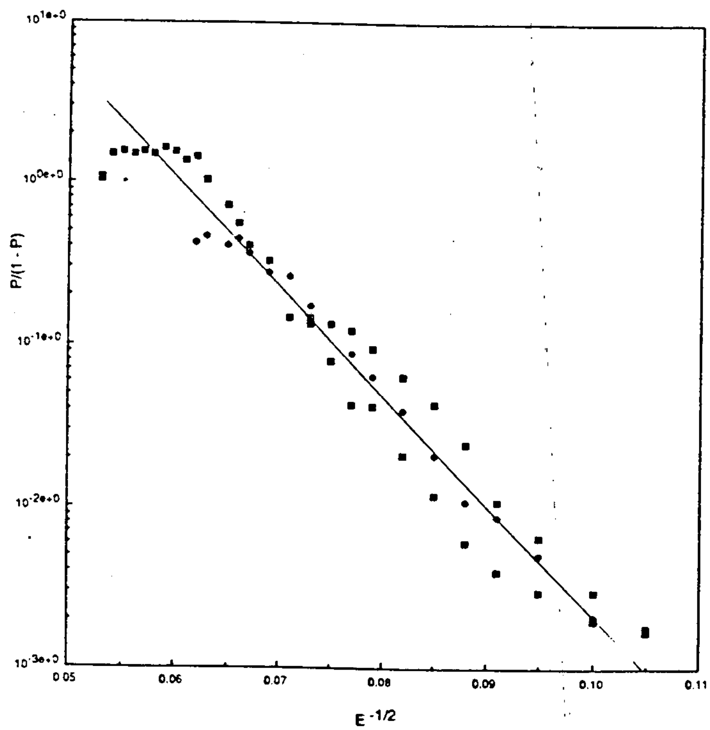


Fig. 10 Dependence of the relative three body emission probability P upon excitation energy for the reaction ^{100}Mo + ^{100}Mo at various bombarding energies.[9] The linearity of this particular plot indicates statistical emission.

there are honest-to-goodness compound nuclei in the exit channel which decay as such, not only insofar as the common n, p, and α particle channels are concerned, but also with respect to the more exotic complex fragment emission as well.

Coming back to γ rays, the experiment measured them up to 60 MeV of energy and for 10 bins of total kinetic energy loss. The ungated γ rays look very much like those measured in other reactions and interpreted in terms of nucleon-nucleon bremsstrahlung. However, when these spectra are gated with different bins of total kinetic energy loss (TKEL), a very surprising picture emerges, suggesting an exit channel rather than an entrance channel origin.

In Fig. 11 three spectra are shown covering the total kinetic energy loss range of the experiment. Notice how the high excitation energy bin is associated with the stiffest γ-ray tail while the low excitation energy bin is associated with the softest. In Fig. 12a this is shown better by plotting the slope parameters vs the TKEL. The square root-like dependence is very suggestive and one is tempted (and should be!) to interpret the slope parameter as a temperature. Similarly, the integrated multiplicites with two different lower bounds of 15 and 30 MeV γ-ray energies shown in Fig. 12b, when plotted vs the fragment excitation energy, reveal a dependence typical of compound nucleus decay.

This evidence does not come totally unexpected. We <u>know</u> that there are two compound nuclei in the exit channel. We know that they decay as such by light particle emission and by complex fragment emission. Why should they not decay by γ-ray emission? <u>Perhaps</u> there are additional sources for the γ rays, like incoherent bremsstrahlung, etc., but we know <u>for sure</u> that <u>those compound nuclei must emit γ rays.</u> So let us calculate this emission. We can calculate the γ decay width in an "almost" model independent way from detailed balance and the inverse cross section:

$$P(\varepsilon_\gamma) = \frac{\Gamma(\varepsilon_\gamma)}{\hbar} = \frac{8\pi}{c^2 h^3 \rho(E)} \sigma(\varepsilon_\gamma)\, \rho(E-\varepsilon_\gamma)\, \varepsilon_\gamma^2 \tag{2}$$

$$\cong \frac{8\pi}{c^2 h^3} \sigma(\varepsilon_\gamma)\, \varepsilon_\gamma^2\, e^{-\varepsilon_\gamma/T} . \tag{3}$$

The inverse cross section is fairly well known experimentally. In the low energy region between 6 - 20 MeV, it is dominated by the giant dipole resonance, while above that the quasi deuteron mechanism prevails. The temperature T can be calculated from the excitation energy as $E_x = aT^2$.

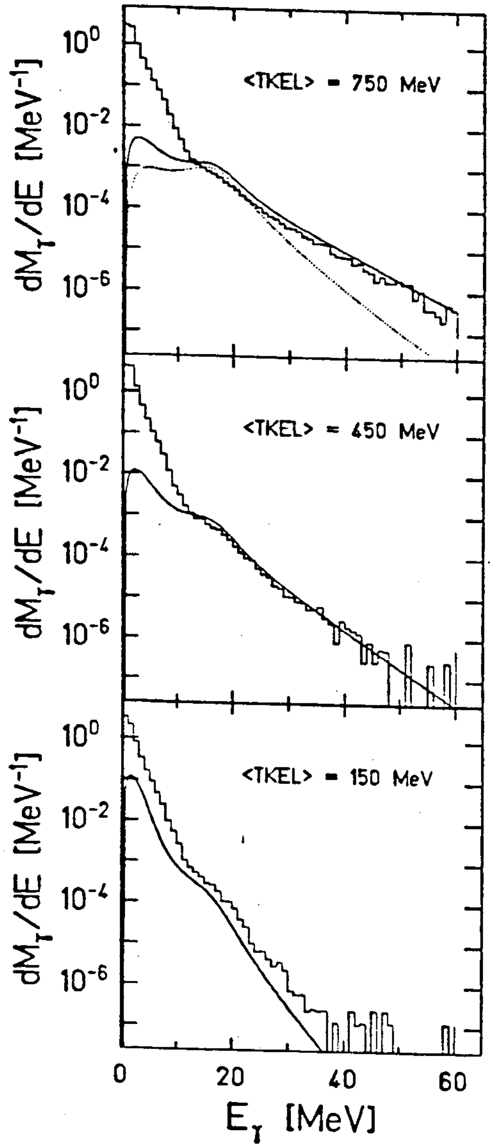


Fig. 11 Gamma ray spectra for three different bins in total kinetic enegy loss. The solid curves represent statistical model calculations. The dotted curve curve is obtained in the same way as the solid curve except for the elimination of the quasideuteron component in the γ-cross section.

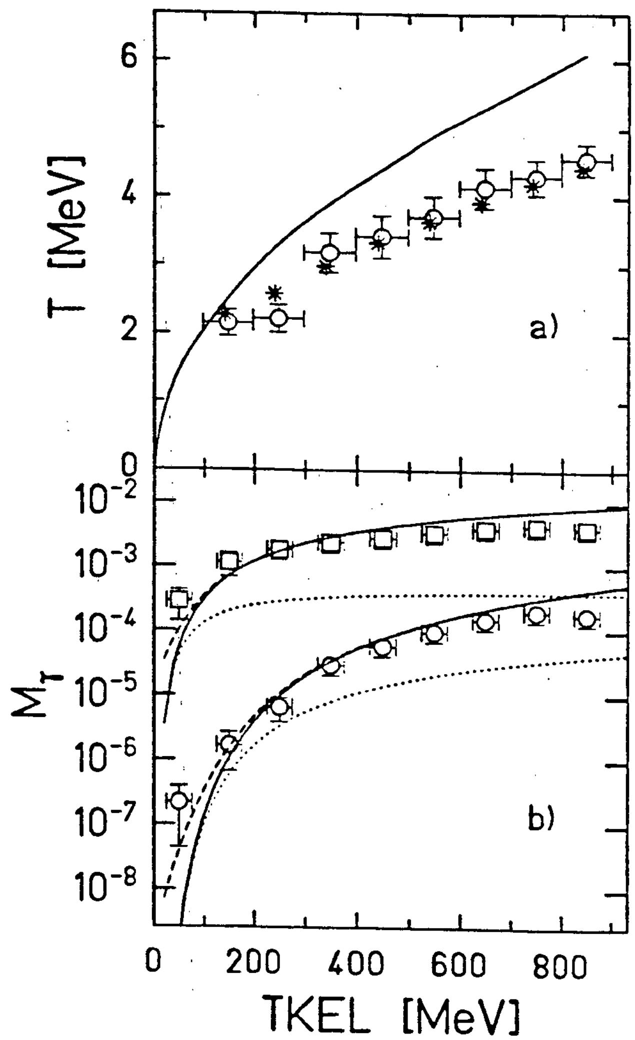


Fig. 12 a) "Temperatures" of Boltzman fits to measured (open circles) and calculated (stars) γ spectra. The solid line denotes the primary temperature of the fragments which has been calculated from the energy loss. b) Experimental and theoretical multiplicities of hard photons with energies ≥ 15 (squares) and 30 MeV (circles), respectively. The different lines are the result of a statistical model calculation and show the first chance contribution (dotted line), the sum over all generations (solid line) and the effect of the experimental binning of the excitation energy (dashed line).

In the actual decay, γ emission competes with n, p and α particle emissions which can be calculated in a similar fashion. In this way we can generate the "first chance" γ ray emission probability vs excitation energy:

$$P_\gamma(\varepsilon_\gamma) = \frac{\Gamma(\varepsilon_\gamma)}{\Gamma_T} \cong \frac{\Gamma(\varepsilon_\gamma)}{\Gamma_n + \Gamma_p + \Gamma_\alpha + ...} \quad (4)$$

At this point one proceeds trivially to calculate the 2^{nd}, 3^{rd} etc. chance emission probability. The overall sum can be compared with experiment. In Fig. 11 we see that this calculation reproduces the spectra from 15 MeV γ-ray energy up to 60 MeV almost perfectly for all the energy bins, both qualitatively and quantitatively. The slope parameters can also be compared with the data. This is shown in Fig. 12a and again the fit is essentially perfect. The solid line in the figure represents the initial calculated temperature. The actual slope parameter is somewhat smaller due to the substantial presence of higher chance emission at the highest energies. Similarly the integrated γ-ray multiplicities are equally well reproduced by the calculation, as can be seen in Fig. 12b. The inescapable conclusion is that all of the γ rays observed experimentally actually come from the statistical emission of the fragments. No room is left here for any other mechanism!

Somebody might object by saying, and perhaps by showing, that "other" theories fit the data almost as well and that there is no reason to choose one "theory" over another. The point is that our calculation is really no theory to speak about. We know that there are two compound nuclei in the exit channel, emitting light particles and complex fragments, because their decay products have been measured and their statistical properties verified. Therefore, we know that these compound nuclei must also emit γ rays. All we have done is to calculate, as it were, the "background" γ rays coming from compound nucleus decay. Any other "theory" can be tested only after this "background" has been substracted. In this case nothing is left and the matter is settled.

It would be interesting to check how much of the $\pi^0, \pi^\pm$ production in intermediate heavy ion reactions can be explained in terms of emission from the compound nuclei present in the exit channel. Unfortunately, this will have to wait for more complete experiments, although it is an easy guess that, in certain low energy reactions, the compound nucleus contribution may not be negligible and must be evaluated.

Conclusions

There is one thing worse than not discovering a new process or mechanism, and that is of discovering it when it is not there!

Acknowledgements

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